# A HIGH GRANULARITY TIMING DETECTOR FOR THE PHASE-II UPGRADE OF THE ATLAS CALORIMETER SYSTEM: BEAM TEST RESULTS

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8th BTTB, 27-31 January, Tbilisi

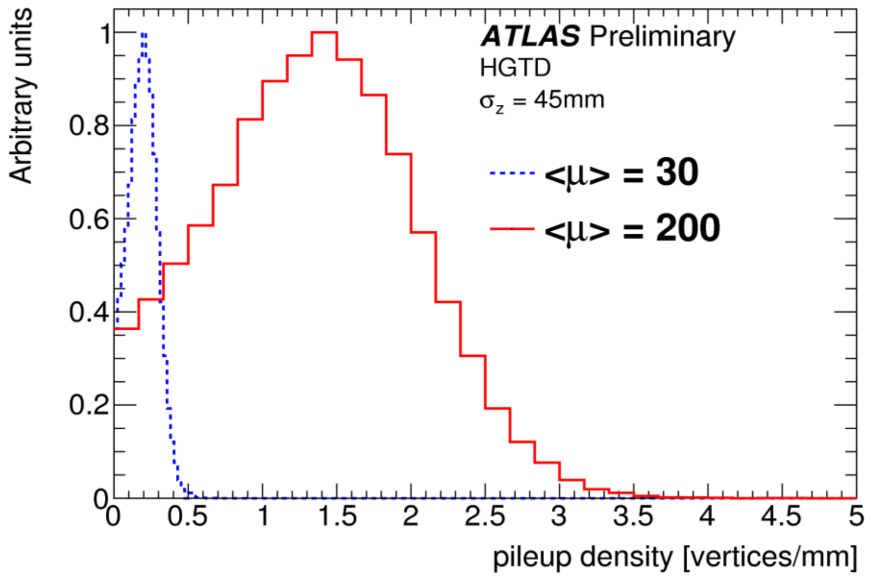
# Overview

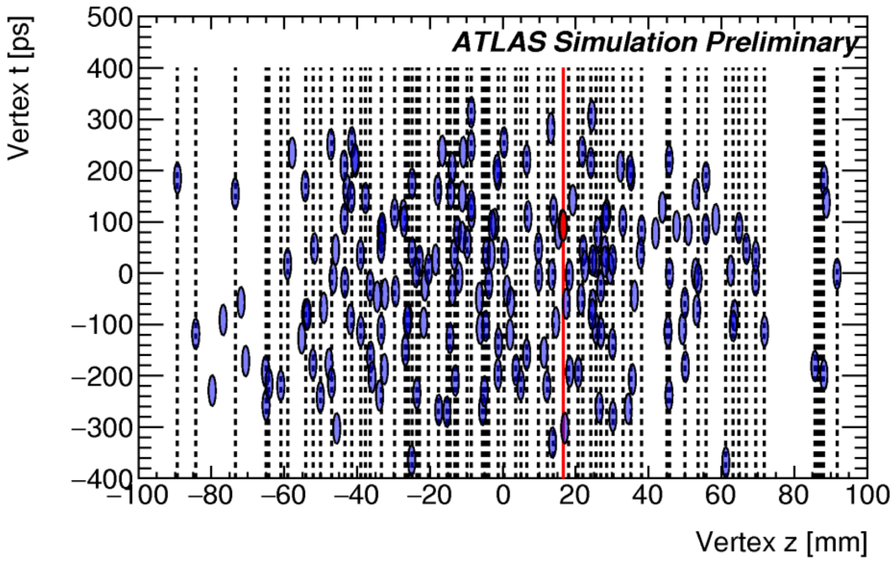
- HGTD motivation and requirements
- Low Gain Avalanche Detector technology
- HGTD test beam campaigns
- Results
- Summary and outlook

# **HGTD** motivation

## HL-LHC Phase

- Instantaneous Luminosity up to $L \approx 7{,}5\ \times 10^{34}\ cm^{-2}s^{-1}$ ($\times$ 5 current $L_{inst}$)
- Pile-up challenge:
  - $< \mu > = 200$ interactions per bunch crossing!
  - $\sim 1{,}8$ collisions/mm on average
- Particle density increase:
  - Coarser granularity in LAr calorimeter
  - New ATLAS Inner Tracker (ITk) will provide coverages up to $|\eta| = 4{,}0$
  - Decrease of z vertex reconstruction and physics object performance in the forward region
- **H**igh **G**ranularity **T**iming **D**etector (HGTD) proposed in front of the end-cap calorimeter for pile-up mitigation
- Performance improvement by combination between
  - HGTD timing
  - ITk position information





# High Granularity Timing Detector

- Detector located in an unoccupied region in front of the end cap calorimeter
- Thickness in $z = 75\ mm$ , Radial extension $120\ mm < R < 640\ mm$, $2{,}4 < |\eta| < 4{,}0$
- Two double-side layers mounted on cooling disk
- Average number of hits per ring: 2,7 – 2,5 – 2,1

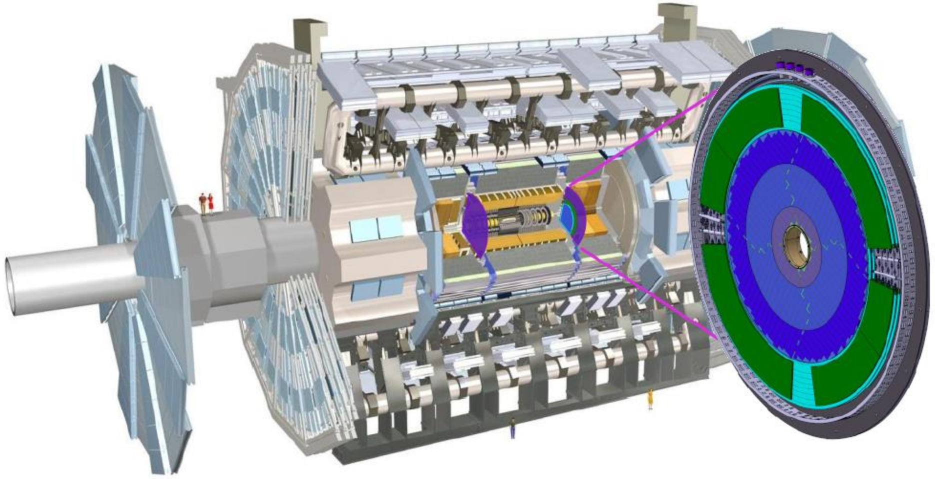
## Time resolution

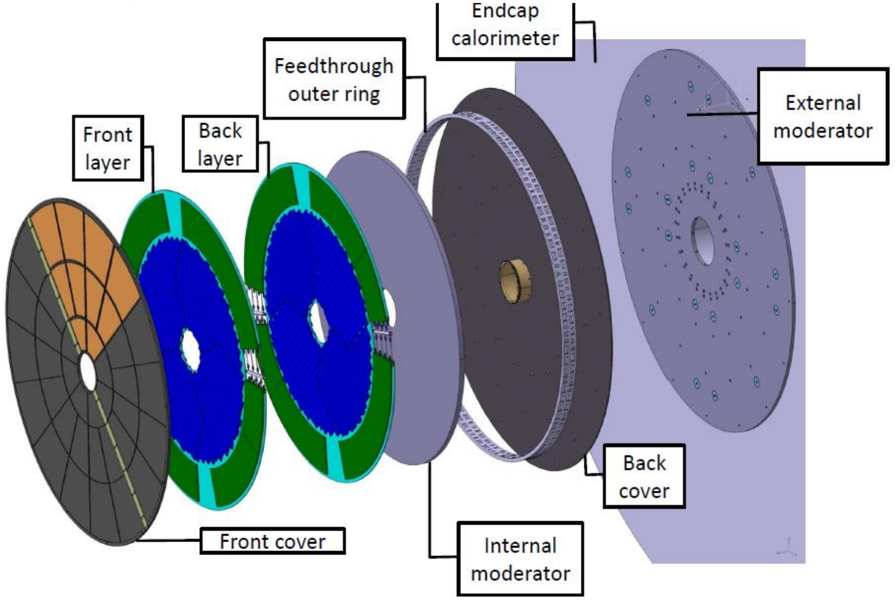
- $\sim$30 ps resolution per track ($\sim$50 ps per hit) in a two layer geometry
- To reduce tracks association with hard scattered jets

## Technology

- Instrumented with Silicon based **L**ow **G**ain **A**valanche **D**etectors (LGADs)
- Front-end electronics: **A**TLAS **L**GAD **T**iming **R**ead**O**ut **C**hip (ALTIROC)

## Total active area $6,4\ m^2$





# **HGTD** design concepts

## Coverage

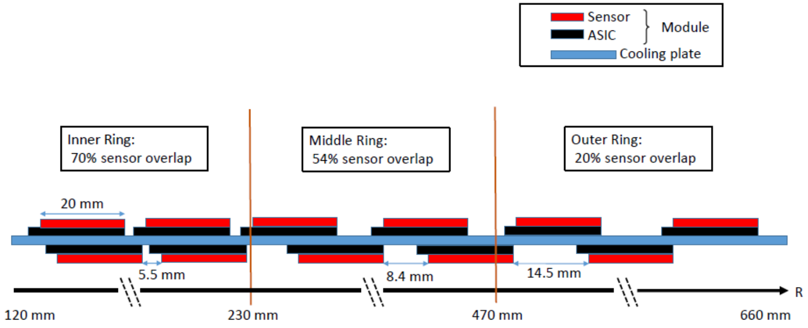
- Module overlap between layer sides optimised for uniformity
- Disk rotation in opposite direction to avoid gaps

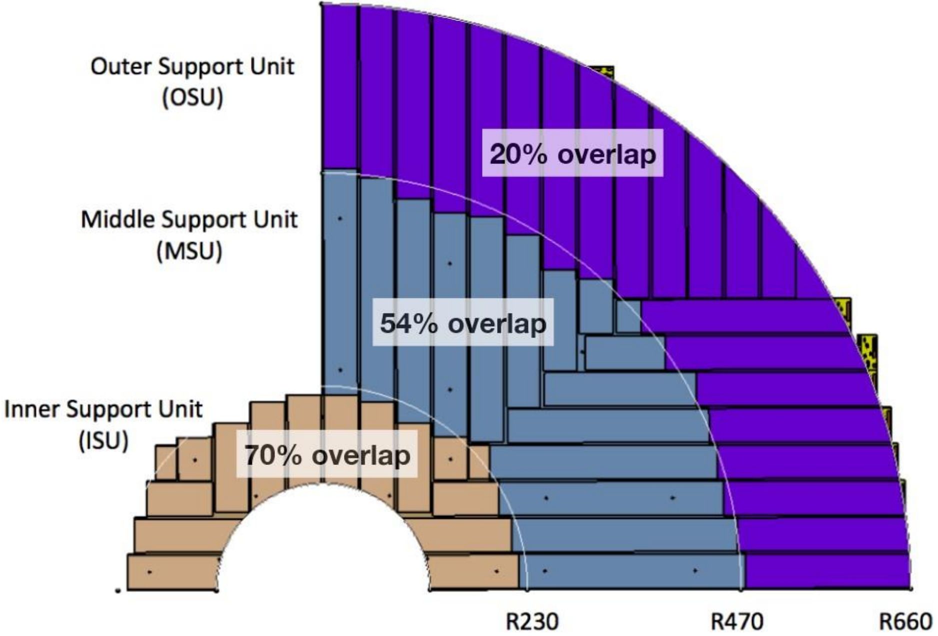
## Radiation effects

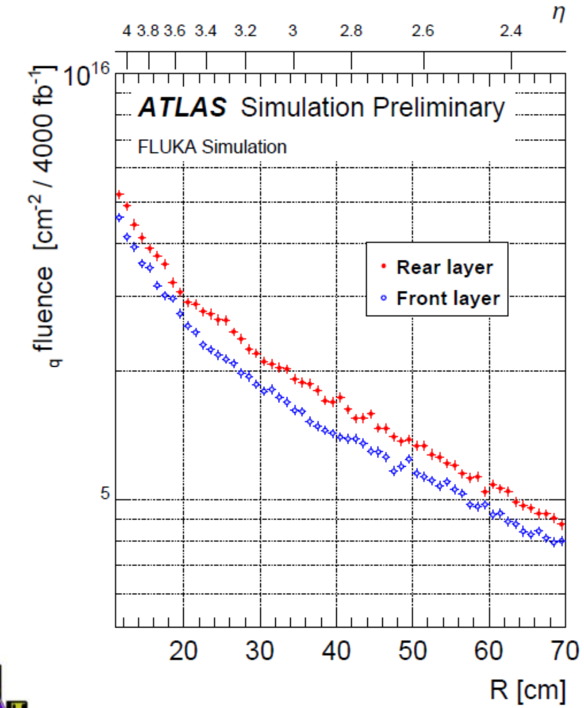
- $\sim 4000\ fb^{-1}$ in HL-LHC lifetime
- Three ring layout
  - Inner ring replaced every $1000\ fb^{-1}$
  - Middle ring replaced after $2000\ fb^{-1}$
- Total Ionizing Dose (TID): $2\ MGy$
- Fluence: $2{,}5 \times 10^{15}\ n_{eq}/cm^2$

## Operation

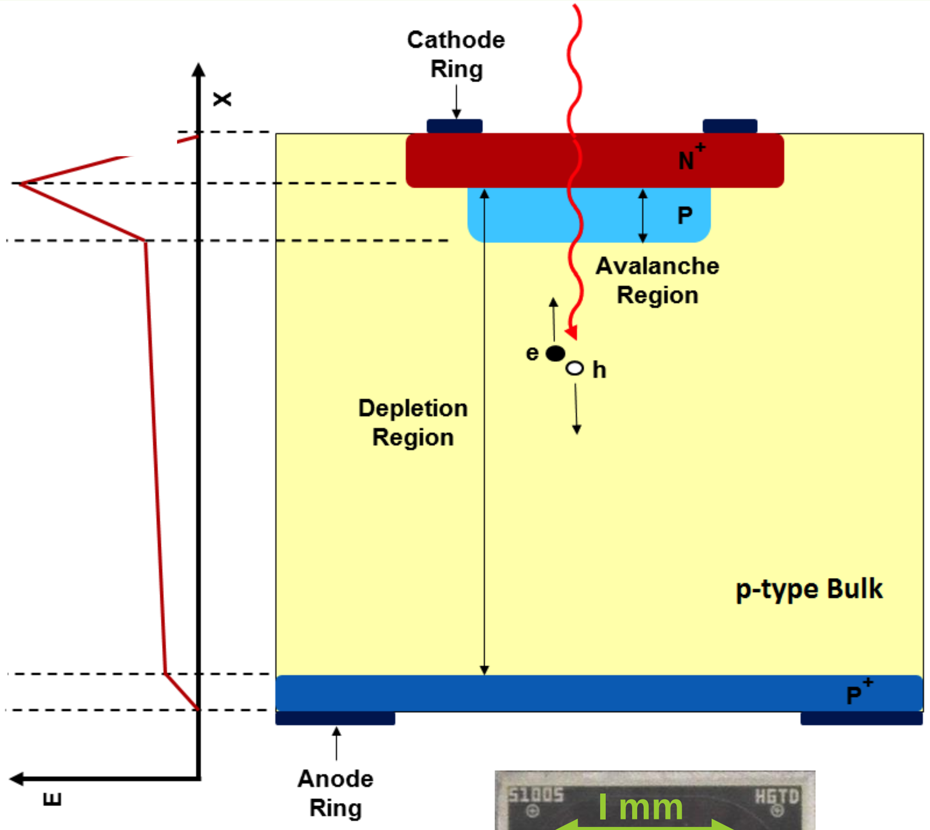
- Sensors will be operated at -30 °C using a common $CO_2$ cooling system with ITk

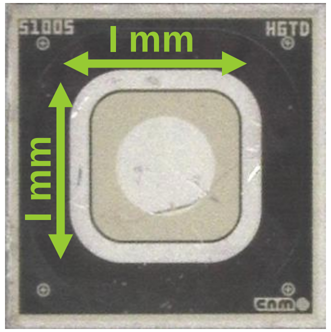






# Low Gain Avalanche Detectors (LGADs)





CNM LGAD for HGTD

## Pioneered by Centro Nacional de Microelectrónica (CNM)

- n-on-p silicon detector
- Signal amplification provided from the extra doped p-layer below the n-p junction
- High E field
- Internal gain: ~ 10-50 (large S/N ratio)
- Typical rise time: ~ 0,5 – 0,8 ns
- Time resolution before irradiation < 30 ps
- $50\ \mu m$ thick sensors → faster rise time and lower impact from radiation

## R&D program

- Provide sensors meeting the time resolution, gain and radiation hardness requirements
- 50 $\mu m$ thin LGAD chosen as baseline
- Different doping material (B, Ga, B+C)
- Different manufacturers: CNM, HPK, FBK, BNL and IHEP-NDL
- Interest to study LGAD performance at high fluences beyond $10^{15}\ n_{eq}/cm^2$
- Test beam results will be presented for a CNM Gallium doped LGAD sensor irradiated to $\mathbf{3 \times 10^{15}\ n_{eq}/cm^2}$

# HGTD Test beam Campaigns

**2016**
**CERN SPS**

Un-irradiated sensors, 120 GeV pions

**2017**
**CERN SPS**

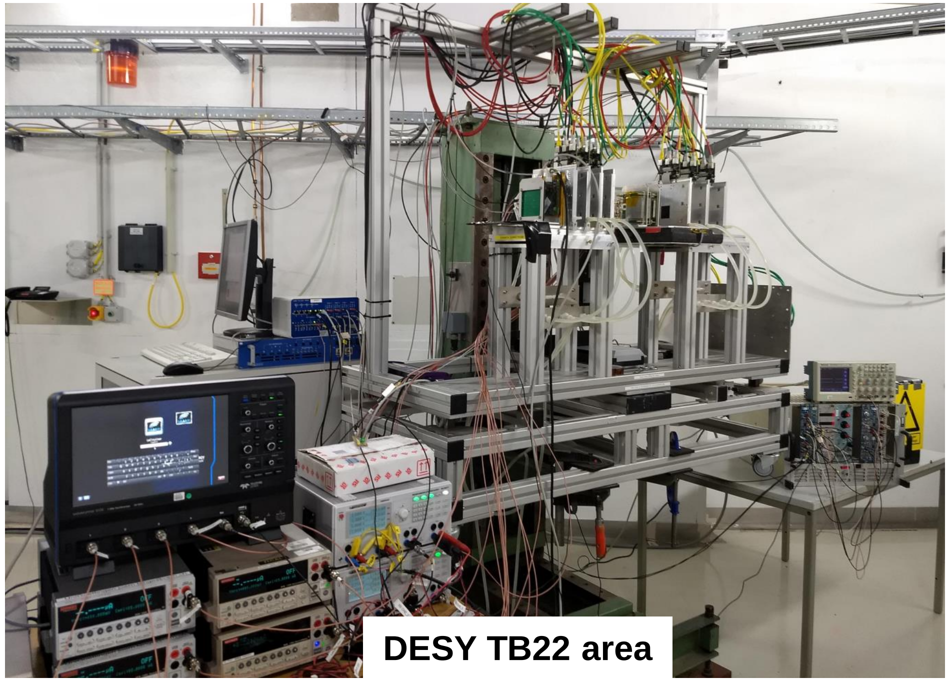
Un-irradiated and irradiated CNM and HPK single pads and arrays, 120 GeV pions. Paper: **2018 JINST 13 P06017**

**2018**
**CERN SPS**

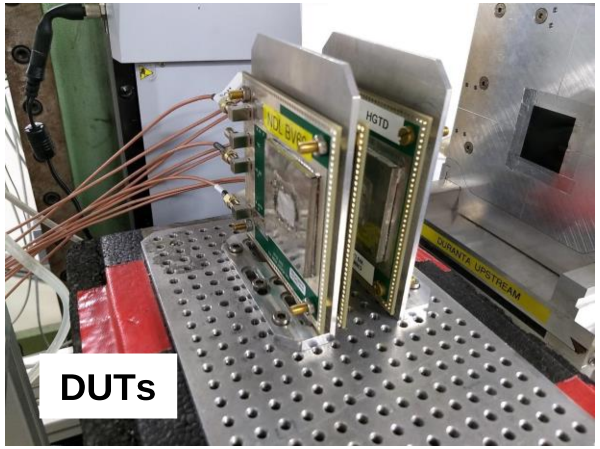
CNM, HPK and BNL sensors, different dopings, 2×2 sensor with ALTIROC0_v2, arrays with different nominal gap, 80 - 160 GeV pions

**2019**
**DESY**

CNM, HPK, FBK and NDL sensors, n and p irradiated and un-irradiated single pads and arrays, ALTIROC1_v2 coupled to a sensor, 5 GeV electrons



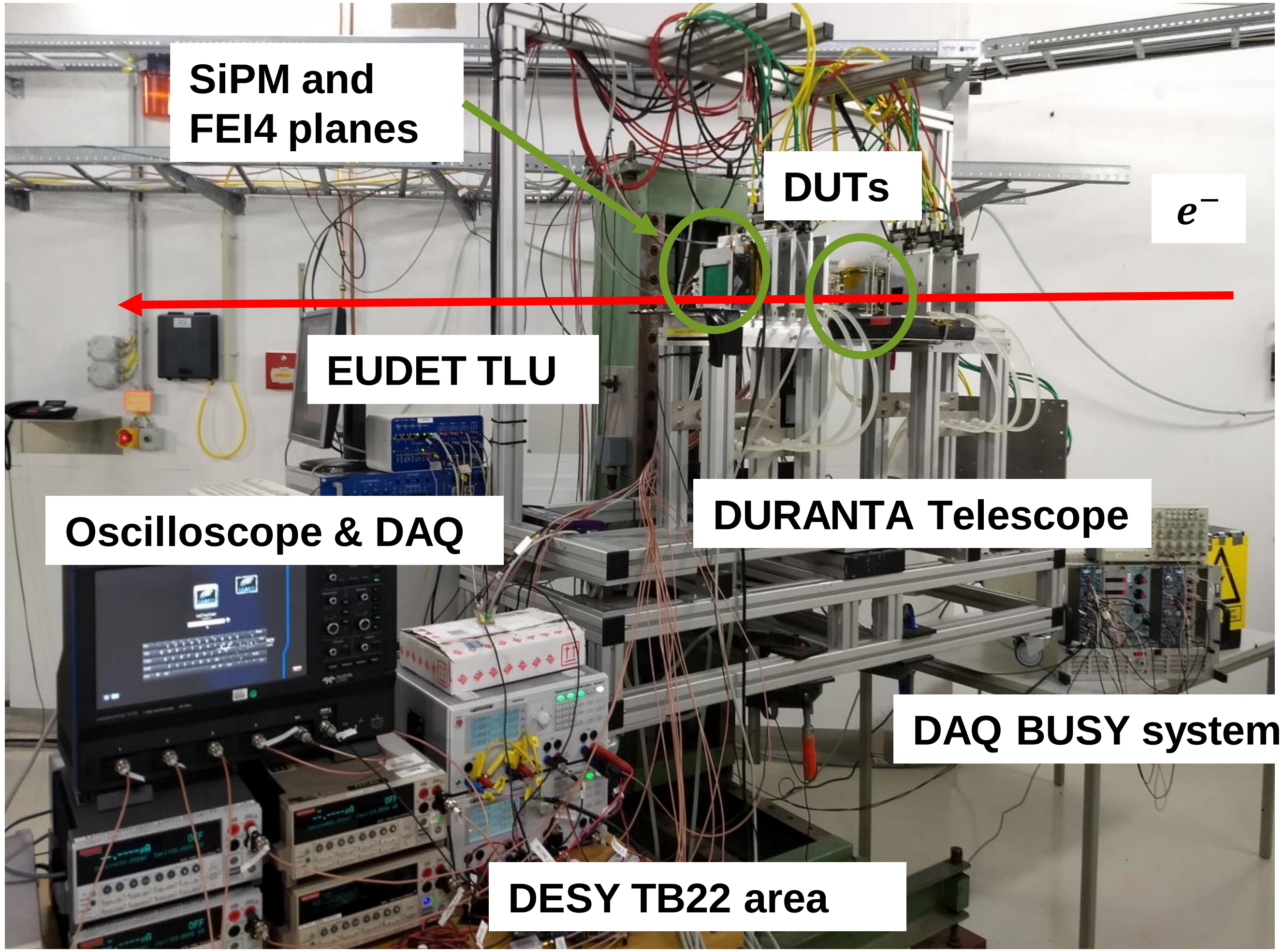
**DESY TB22 area**



**DUTs**

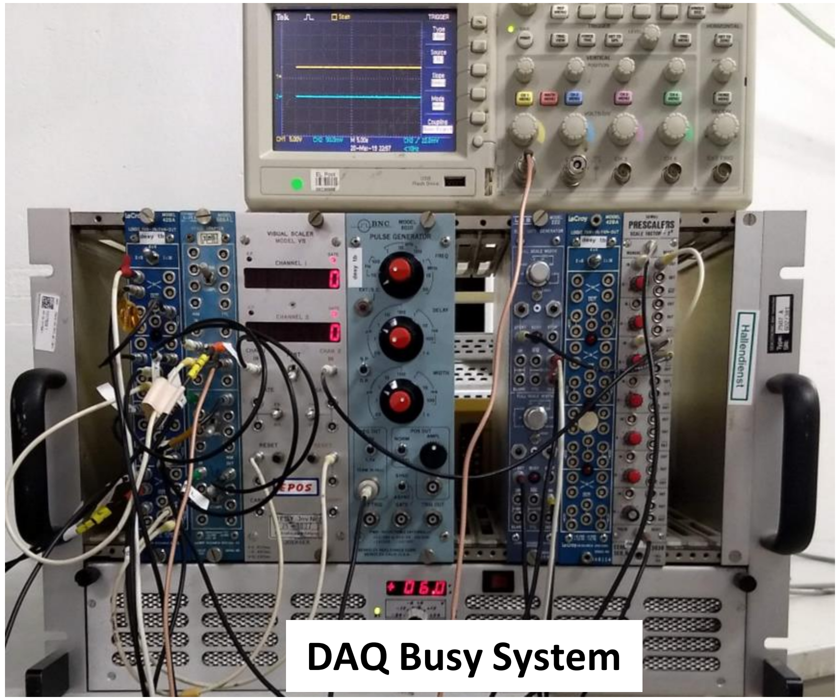
# Test Beam DAQ and trigger

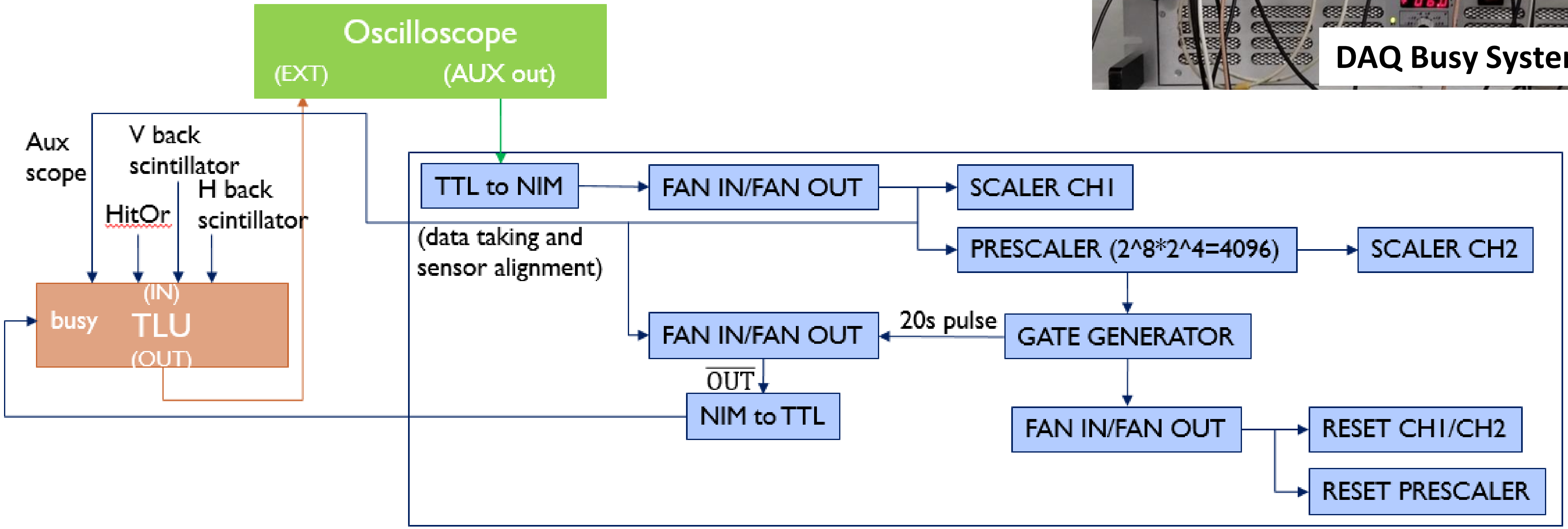
- FE-I4 plane used as a trigger reference for data taking
- Definition of a ROI mask in the FE-I4 plane
  - Only accepts track passing trough this area which cover all LGADs position
  - Use of inverted signal from FE-I4 HitOr (TTL → NIM)
- $\sim$100 ns delay on scintillator signal to match HitOr signal in the TLU trigger window
- 5 ns trigger window in the TLU
  - Triggers oscilloscope
  - MIMOSA readout
  - MMC3/USBpix
- Oscilloscope in segmented mode with time delay
  - When electrons hit the LGAD the oscilloscope retrieves corresponding waveforms
- DUTs on PI stage in  a cooling box with dry ice



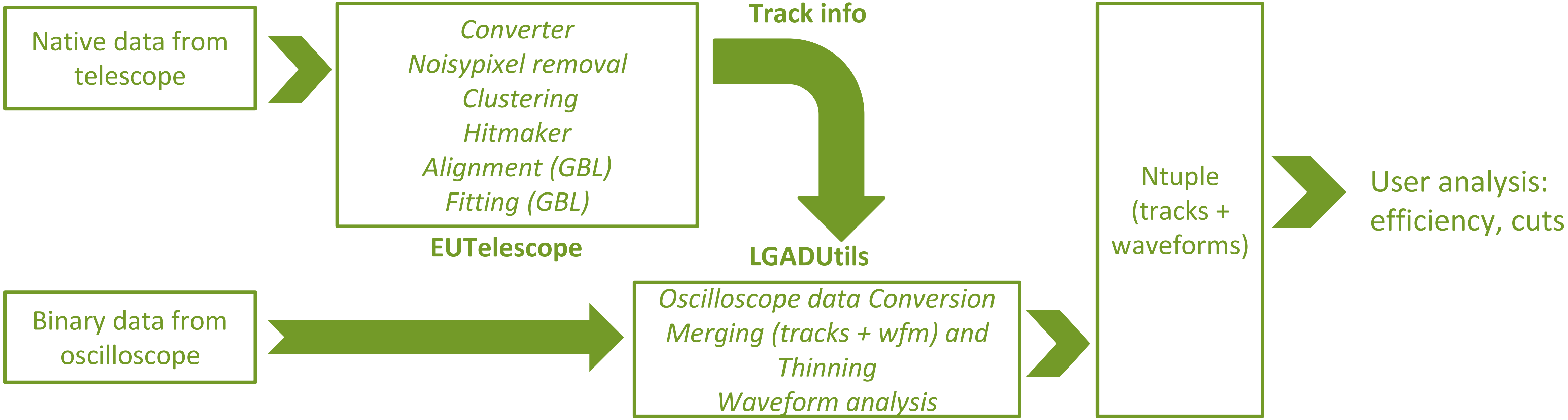
# DAQ BUSY signal

- Continuous beam at DESY
  - Oscilloscope needs time to empty the buffer
  - Need to simulate the SPS spill-like
  - NIM electronics BUSY (20 s long pulse) system assembled for this purpose (Thanks to DESY support!)
  - BUSY signal is input in the TLU and acquisition will be paused for 20 s


**DAQ Busy System**


Oscilloscope
(EXT)
(AUX out)
Aux scope
V back scintillator
H back scintillator
HitOr
(IN)
busy
TLU
(OUT)
TTL to NIM
(data taking and sensor alignment)
FAN IN/FAN OUT
SCALER CH1
PRESCALER (2^8*2^4=4096)
SCALER CH2
GATE GENERATOR
20s pulse
FAN IN/FAN OUT
$\overline{\text{OUT}}$
NIM to TTL
FAN IN/FAN OUT
RESET CH1/CH2
RESET PRESCALER

# Track reconstruction and analysis framework



Native data from telescope

*Converter*
*Noisypixel removal*
*Clustering*
*Hitmaker*
*Alignment (GBL)*
*Fitting (GBL)*

**EUTelescope**

**Track info**

**LGADUtils**

Binary data from oscilloscope

*Oscilloscope data Conversion*
*Merging (tracks + wfm) and*
*Thinning*
*Waveform analysis*

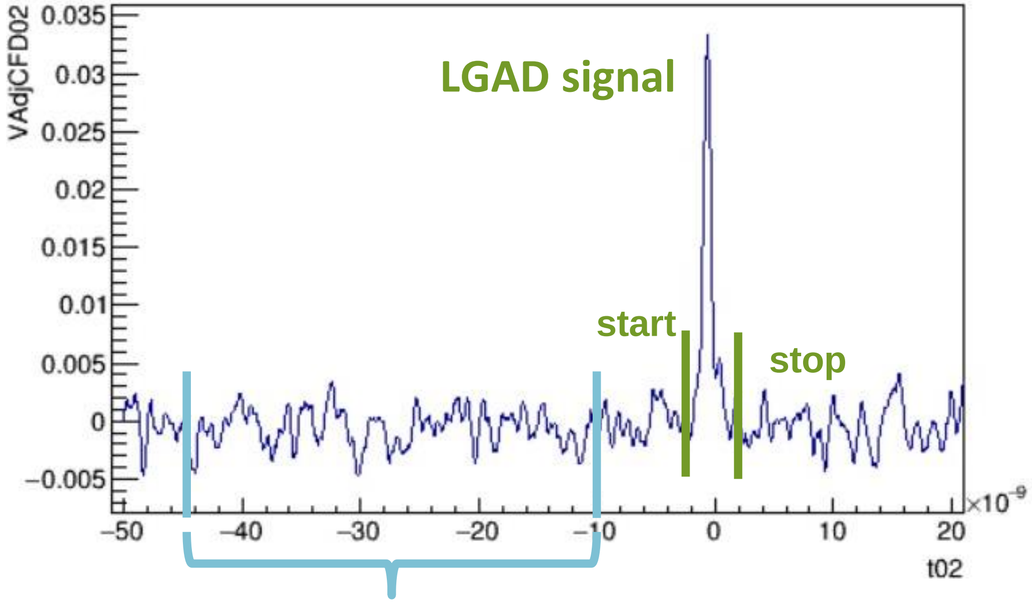
Ntuple (tracks + waveforms)

User analysis: efficiency, cuts

- Track reconstruction with **EUTelescope v01-19-02 using GBL algorithm** asking one hit in the FE-I4 plane
- Resulting ~30% of the events with average FE-I4 efficiency of 99.6%
- Waveform processing performed with **LGADUtils framework** (C++ based) developed at IFAE by V. Gkougkousis
    - Git repository: **https://gitlab.cern.ch/ifaepix/lgad-timing-analysis/**
- Match event between telescope and oscilloscope drop off event with no FE-I4 information

# **LGADUtils** framework

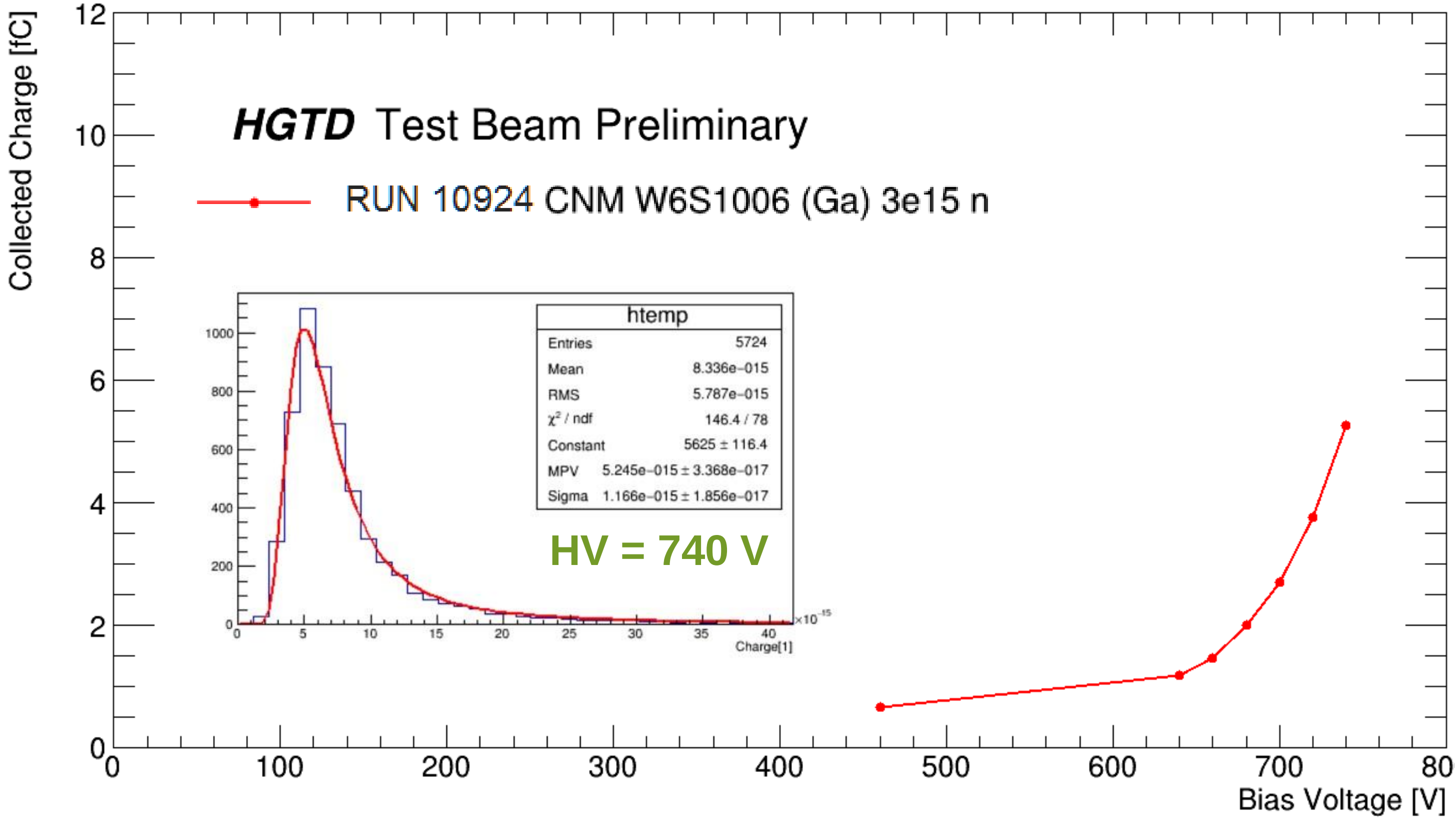
- C++ based
- Working with Root v5-v6, different operating system
- Steps
  - Conversion oscilloscope binary data to Root ntuple with raw waveform information
  - Merging with track ntuple from EUTelescope
  - Waveform analysis
    1. Determination of pulse polarity, signal start and stop, determine if the pulse is noise or signal
    2. Calculate noise level and pedestal using Gauss fit, pedestal substraction, recalculation of start and stop of the signal
    3. Compute charge, rise time, time at different CFD fractions…
    4. Perform CFD Time Walk correction
  - User analysis
    1. Efficiency



Noise and Pedestal calculation

# Collected charge vs bias voltage

**CNM Gallium LGAD sensor W6S1006 $3 \times 10^{15}\ n_{eq}/cm^2$**



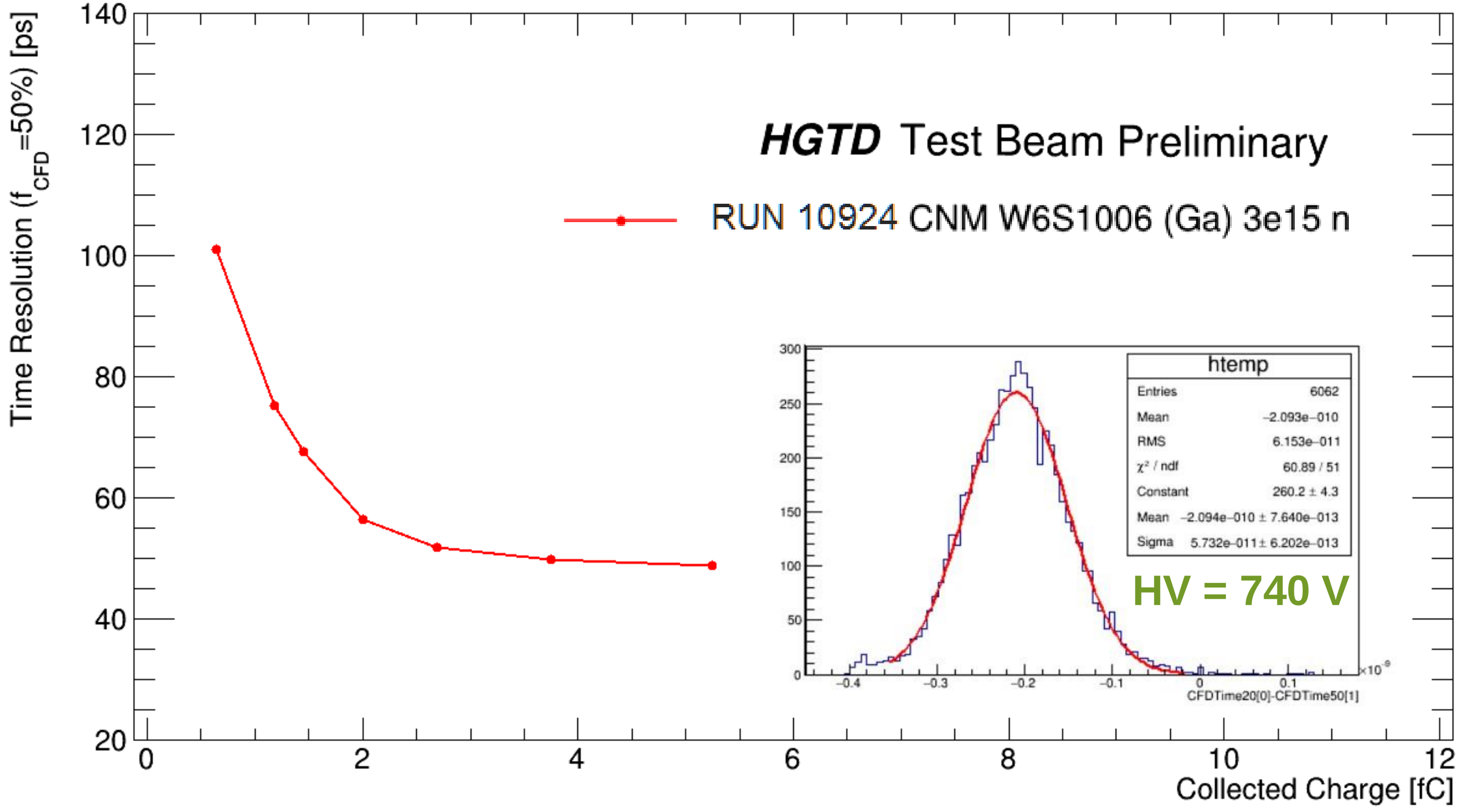
- ○ Charge calculated as the integral of the signal area for each waveform after pedestal substraction

- ○ For each voltage point the collected charge is given by the MPV value of the Landau-Gauss fit of the events charge distribution

- ○ Collected Charge:
  - Bias voltage range: 460 V to 740 V
  - 2 fC at ~ 680 V
  - Reaches 4 fC for optimal ALTIROC performance for bias voltage > 720 V

# Time resolution vs collected charge

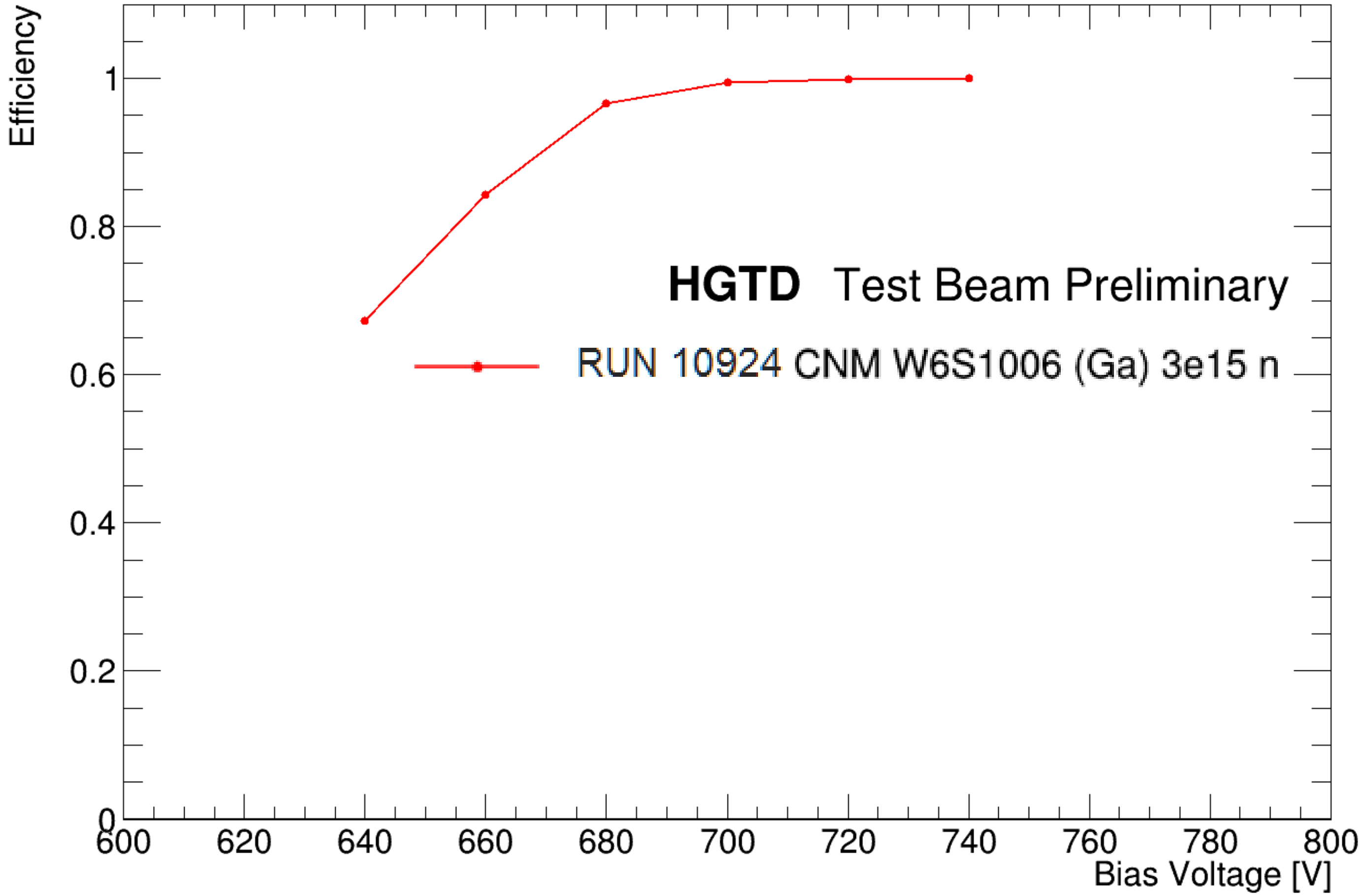
**CNM Gallium LGAD sensor W6S1006 $3 \times 10^{15}\ n_{eq}/cm^2$**



- Calculated as the difference between the time at $f_{CFD}$=50% for DUT and the time at $f_{CFD}$=20% for the unirradiated LGA35 (reference time sensor)
  $\Delta t = t_{DUT(f_{CFD}=50\%)} - t_{LGA35(f_{CFD}=20\%)}$
- The time difference distribution is fitted with a Gaussian with the time resolution of the system defined as the $\sigma$ of the Gaussian
- The contribution of the LGA35 is subtracted (~29,7 ps at -28° C)
- At ~ 740 V time resolution is ~ 48 ps

# Efficiency vs bias voltage

**CNM Gallium LGAD sensor W6S1006 $3 \times 10^{15}\ n_{eq}/cm^2$**



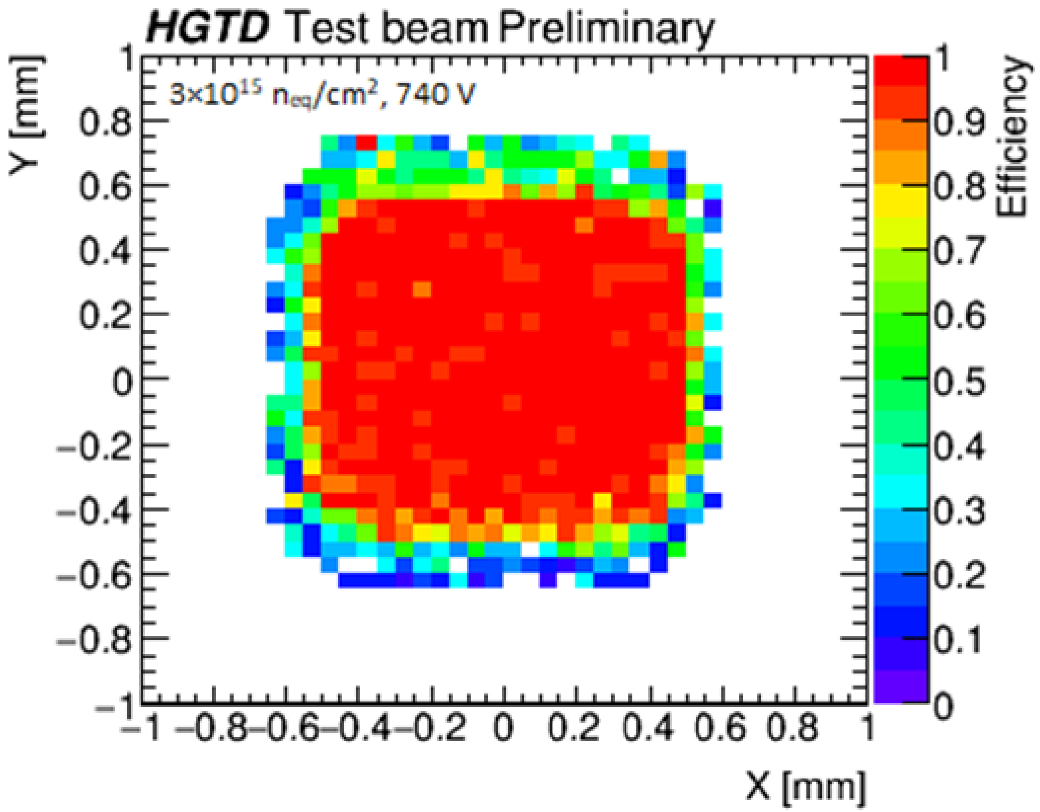
- Effciency is defined for each bias voltage point as:

$$\varepsilon = \frac{Tracks\ in\ the\ ROI\ with\ signal > 10\ mV}{Tracks\ in\ the\ ROI}$$

- For HV > 700 V → Efficiency > 99%
- 10 mV threshold chosen because is more than $5\sigma$ over the noise
  - Assuming a median noise level of 2 mV

# 2D map efficiency for **$\mathrm{HV}_{\mathrm{BIAS}}$ = 740 V**

## CNM Gallium LGAD sensor W6S1006 $3 \times 10^{15}\ n_{eq}/cm^2$



- ○ Efficiency map for 740 V is defined as

$$\varepsilon = \frac{Tracks\ with\ Q > 2\ fC}{Total\ number\ of\ Tracks}$$

- ○ Q > 2 fC threshold corresponds to ~15 mV for this voltage point
- ○ HGTD electronics expected to start to be efficienct for charge bigger than 2 fC
- ○ Average efficiency in the central $0{,}5 \times 0{,}5\ mm^2$ area is **99,1%**

# Summary and outlook

- HGTD detector is proposed in ATLAS for pile-up mitigation during the HL-LHC phase
- HGTD community is investigating LGAD performance at higher fluences ($3 \times 10^{15}\ n_{eq}/cm^2$) and exploring new doping materials
- HGTD community is preparing the TDR, to be submitted to LHCC in April 2020
- Test beam results of a CNM Gallium doped LGAD sensor irradiated to $3 \times 10^{15}\ n_{eq}/cm^2$ are presented
- Parameters as collected charge, time resolution and efficiency are studied and are close to the HGTD requirements
- Four test beam periods are foreseen this year at DESY to test new sensors ad electronics

# BACKUP

# **HGTD** motivation

## HL-LHC Phase

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- Performance improvement by combination between
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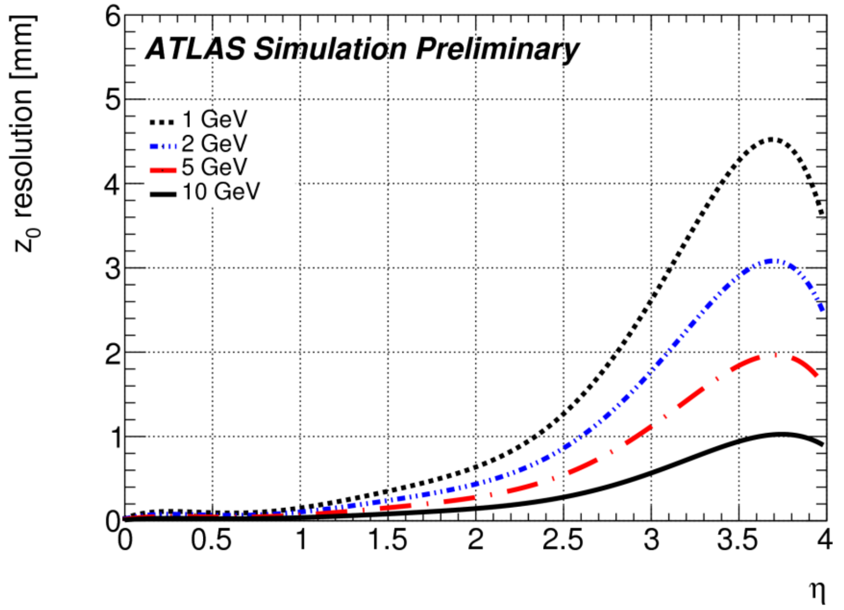
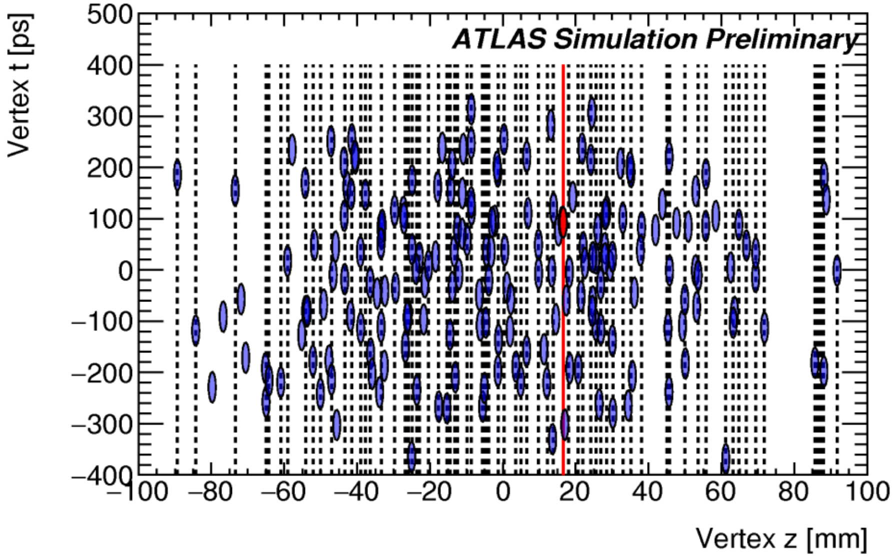
  - ITk position information

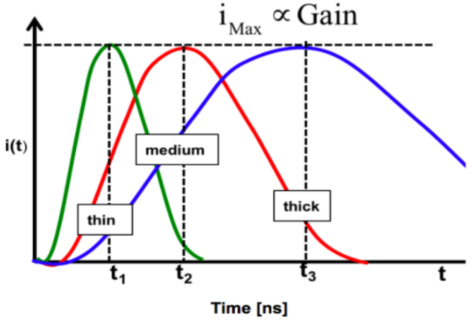


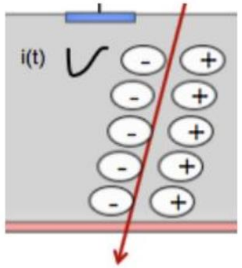


# Timing contributions

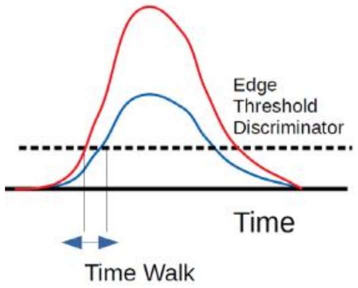
- Landau term $< 25\ ps$
  - Reduce for thin sensors $35 - 50\mu m$
- Jitter term $< 15\ ps$ and time walk correction $< 10\ ps$
  - Low noise and fast signals
- Digitization granularity $\sim 5\ ps$
- Clock distribution $< 10\ ps$

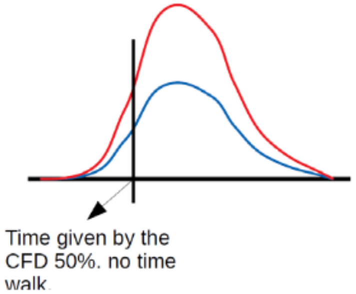
$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \boxed{\underbrace{\left(\frac{t_{rise}}{S/N}\right)^2}_{\sigma_{jitter}^2}} + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$





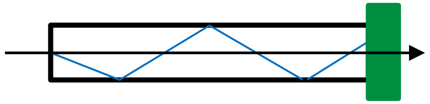
- Time walk correction for test beam data using the **C**ostant **F**raction **D**iscriminator (**CFD**) technique
  - Time at a fraction of 50% of amplitude



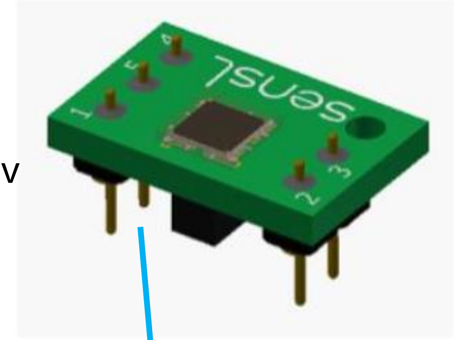


# Timing reference system

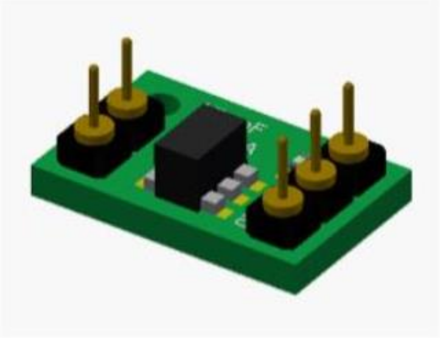
- 4 quartz bars
  - UVFS window
  - $3\times3\times10$ mm$^3$
  - 6 side-polished
- Translucent optical grease
- 4 single channel SIPMs from sensL
  - $4\times4$ mm$^2$ base
  - 0.7 mm thickness
- 4 SIPM readout and amplification boards
  - Shielding for amplification circuitry
- 3D printed quartz light-tight enclosure
  - Main cover and top plate
  - Holes for pins, screws, bar and SIPM



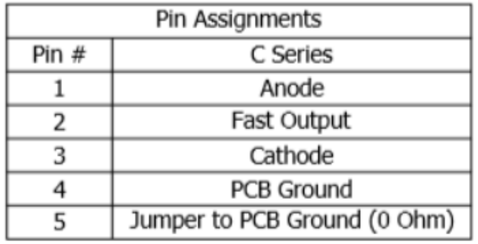
SIPM detects Cherenkov photons generated by charged pions in quartz



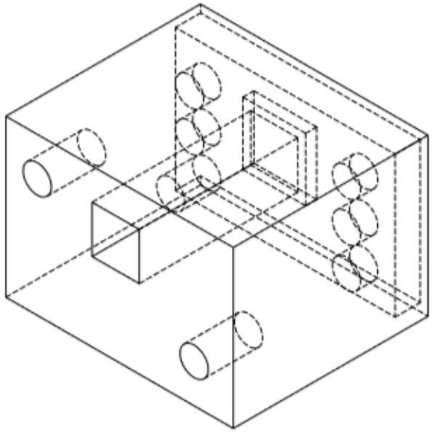
Top View

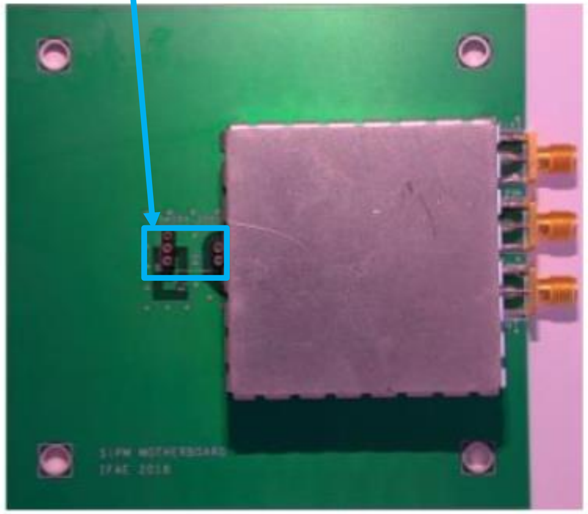


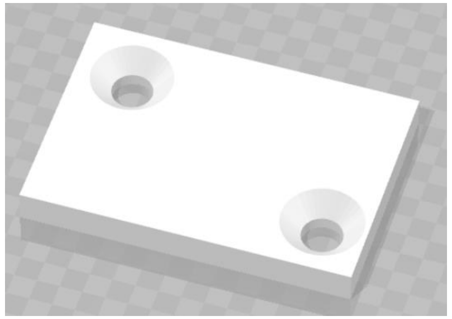
Bottom View



| Pin Assignments | |
|---|---|
| Pin # | C Series |
| 1 | Anode |
| 2 | Fast Output |
| 3 | Cathode |
| 4 | PCB Ground |
| 5 | Jumper to PCB Ground (0 Ohm) |

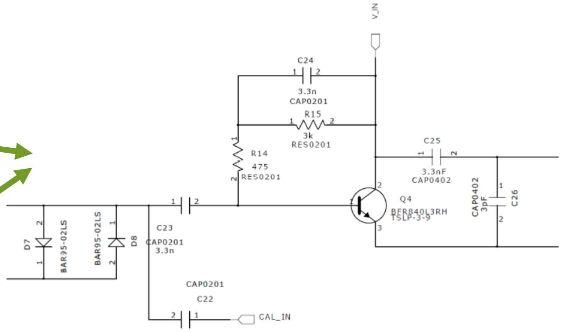


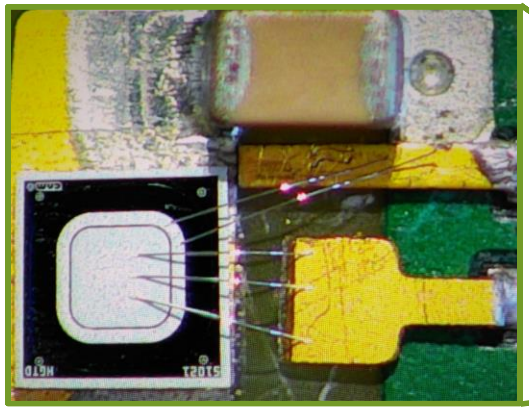


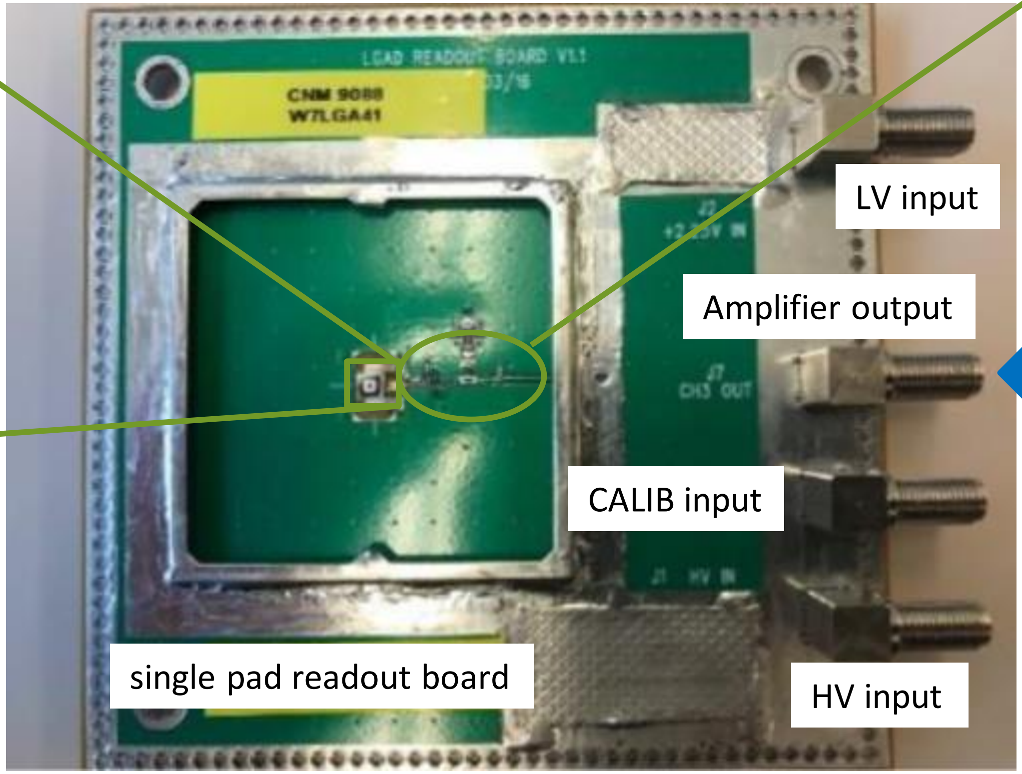


# Sensor and readout board

- More than 50 sensors (un-irradiated, p- and n-irradiated) tested so far
- LGAD readout boards with trans-impedance first stage amplifier
- Voltage second stage amplifiers with hermetic E/B cover design







- Sensor attached to board using double-sided conductive tape
- Amplifier input coupled to metallization layer via wire bonds
- Guard ring grounded

Second stage amplifier output to oscilloscope

- Gain of ~10
- 2 GHz Bandwidth

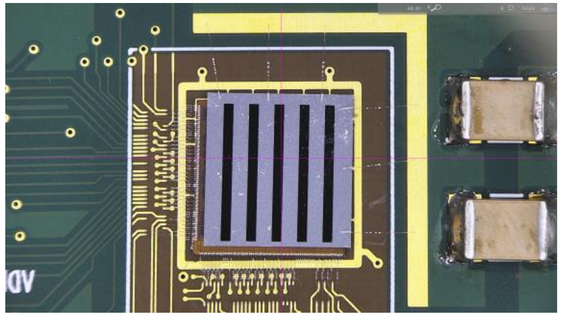
# **ASIC** readout for **HGTD**

## **A**TLAS **L**GAD **T**iming **I**ntegrated **R**ead**O**ut **C**hip (ALTIROC)

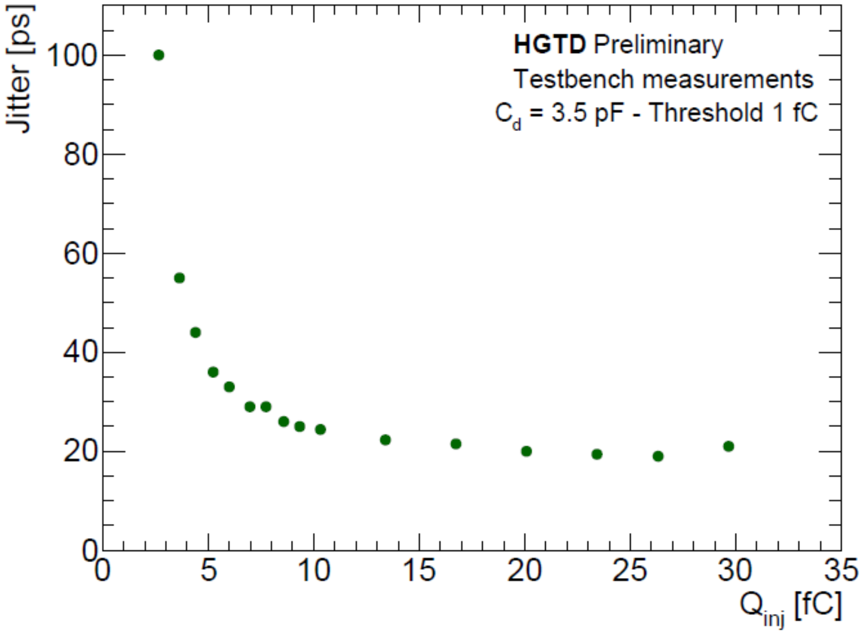
- Minimize noise and power consumption
- Provide **T**ime **O**f **A**rrival (**TOA**) and **T**ime **O**ver **T**hreshold (TOT) measurements
- Readout target time resolution $< 25\ ps$
- $300\ ps$ preamplifier rise time to minimize jitter
- Discriminator threshold can be set for small enough values of input charge
  - Minimum threshold for a 4 fC charge value with efficiency of 95%
  - Time resolution will be dominated by the jitter at high levels of irradiation

## Development

- **ALTIROC 0**
  - Single pixel analog readout (preamplifier + discriminator)
  - Test bench measurements satisfactory
  - Beam test October 2018 @ CERN SPS beam line
- **ALTIROC 1**
  - Full single pixel readout (analog + digital) in $5 \times 5$ arrays
  - Test bench (Jan 2019)
  - Beam test August & November 2019 @ DESY beam line: analysis on going
- **ALTIROC 2**
  - Full version with 15x15 channel readout
  - Available Spring 2020



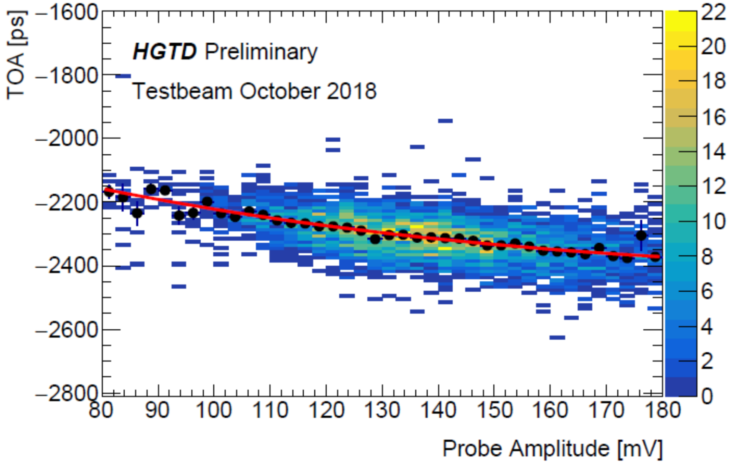
$5 \times 5$ HPK LGAD bumb-bonded to ALTIROC1_v2



# ALTIROC0 performance in test beam

## First results for ALTIROC0 ASIC from test beam

- **2018 October** testbeam at CERN SPS beam line, **120 GeV pion beam**
- 2 × 2 CNM LGAD sensor bump-bonded to ALTIROC0
- TOA as a function of the amplitude of preamplifier probe
  - Fit the profile of 2D distribution (black dots) with a polynomial to correct timewalk effect



- Time resolution of a channel of a 2 × 2 CNM LGAD array as a function of the discriminator threshold
  - Before time walk correction (black dots)
  - After time walk correction (red dots)
  - 40 ps SIPM used as a time reference
  - Time walk correction performed with amplitude of preamplifier probe
  - 30% improvement in time resolution after correction